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Maintenance Management System: Data and Statistics

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Abstract

Maintenance Management Systems, MMS, are developed to assist in the planning and control of road maintenance operations.

The development of the workplan for the maintenance operations requires calculation of the standard rates of production and productivity for each operation performed in a specific environment. These calculations are done at the head office where the province-wide picture of operations can be developed.

The development of standards is based on the analysis of the frequency distributions of production and productivity rates of different maintenance units. These distributions are used, as well, to analyze the effectiveness of maintenance activities and the efficiency of the maintenance units.

In this paper, the statistical, *sampling*, properties of the MMS data which are collected to construct the distributions are discussed. New procedures reflect the *sampling* properties of collected data were developed and used for standard values calculation.

The microcomputer system which facilitates the calculation of the standard planning values were designed. The use of this system permits better analysis and understanding of large volumes of maintenance data, and more efficient planning and control of the maintenance operations.

1/ Introduction

Maintenance expenditures constitute a large portion of a Transportation Department budget. Maintenance Management Systems (MMS) assist different levels of management in the planning and control of maintenance operations and expenditures.

Periodic reports provided by MMS are used by the management of operational units - patrol and aerial supervisors - to monitor and control on-line operations and operation expenditures. The yearly summary reports and inventory information are used by this level of management to develop their workplans and budget.

District and regional managers utilize the aggregated information to control maintenance expenditure and, at the same time, use detailed unit information to manage the operations. The comparative analysis of performance of operational units and historical information are used for this purpose. The head office uses the Maintenance Management System for monitoring and control of Ministry maintenance expenditure. The MMS provides head office with a base for development of quality, quantity and performance standards. However, it has been recognized that the weaker links in maintenance management are "the systems used to estimate the effort level, service level or work quantity standard" [1]. Maintenance Management Systems, as well, provide the engineering community with a tool for learning and analyzing the efficiency and effectiveness of maintenance operations under different conditions. The SHRP studies are designed to effectively collect and analyze this information to improve maintenance techniques and practices.

This paper briefly describes the essential elements of Maintenance Management Systems and defines the statistical, *sampling*, properties of the data used in the development of planning standards. The data are shown to be deficient for the development of standard planning values and for the engineering assessment of the maintenance operation. Possible solutions to overcome the data deficiencies are suggested.

Most transportation agencies collect and use the MMS data in a similar way [1-3]. Even though there are some differences in the structure of collected data, the data often have the same deficiencies. It is recommended that a careful analysis of the statistical properties of the collected data be made before using them for standards development and the engineering assessment of maintenance operations.

2/ Maintenance Management System Databases: Problems

2.1/ MMS Databases

The development of Maintenance Management Systems dates back to the mid-1960s [4,5]. The need for information to control the operations and to develop maintenance standards has influenced the system design. However, they were mainly developed as an extension of the cost accounting system to provide information for expenditure control and audit. This somewhat hampered the development of true management systems. Later modifications, however, improved the initial systems and the structure of their databases.

Maintenance Management Systems are currently used by transportation agencies as a major source of data for the analysis of maintenance activities. The performance data accumulated in the MMS databases are actually production and cost information allocated to specific operations, to a unit performing the operation, and to the location or road where the operation has been performed. The data allocated in such a fashion are the quantity and dollar value of materials used; labour hours and wages spent on each operation and equivalent rental time and cost of equipment utilization.

MMS contain, as well, an inventory database of managed assets such as roads, structures, roadside facilities, appurtenances, buildings, fixtures and other items assigned to a certain operational unit. When available, the specific characteristics of assets, influential to maintenance needs, are stored in the MMS database. The values of these characteristics, when related to the roads, are averaged over the road length. Examples of such characteristics are road age and condition, AADT, drainage system condition, age and condition of the structures, etc. The standard methods of evaluating these conditions are given in the Maintenance Manuals, see for example, Maintenance Manual of Ministry of Transportation of Ontario [6].

The maintenance of roadways is a multifaceted activity involving hundreds of tasks. Despite the more than two hundred operation categories, (see for example, [6]), the classification system still leaves room for variability within one class. The reasons for this lack of uniformity are, primarily, that many different materials are used for the same operation, with the cost of materials and labour varying from one operational unit to another and one geographical location to another; and that only a few operations are performed by specialized crews, the same does most of the pavement, shoulder, and roadside work. To add to the difficulties, recording of this mass of information is done by maintenance, not clerical staff. The staff of the operational units does not in general utilize the MMS information in its everyday work, and uses it to only a limited extent

during the planning stage. This creates a problem in broadening the MMS databases. The common problem of maintenance management systems is the paper work generated for the staff of operational units.

These problems are curtailing somewhat the efforts of maintenance engineers to experiment with the different variables in their effort to develop a better model of the maintenance demand by roads and structures of different ages in different climates and traffic environments.

In the last decade, efforts have been expanded to improve input and reporting facilities so that they may be used by on-line functional units more directly to control operations and expenditures. In the near future, localized data input and editing may become a reality and management may be able to interrogate and use the data for every day operations. It is expected that the automation of data collection and processing will improve the situation.

The deficiencies of existing pavement databases are discussed by many authors, including for example Clyde A. Burke [1]. Burke's conclusions resulted from analysis of MMS of several state departments of transportation and are supported by Ontario's present experience with MMS. Maintenance engineers have identified the desired improvements of databases, which can be classified as follows:

- to improve data quality;
- to decrease the cost of data collection, transmission and storage by eliminating duplication;
- to develop a reference system which is consistent with other available DOT databases, such as the MTO's Pavement Management System (PMS), accident databases, etc.;
- to include in the Maintenance Management System data which would allow the development of better pavement cost and deterioration models.

The SHRP research activity is expected to provide the information for selecting variables which should be included in the databases of Maintenance or Pavement Management Systems. However, as mentioned by Byrd and Sinha [3], "effort can be made by individual highway agencies to develop appropriate databases combining maintenance and improvement activities for long term analysis". This development is a necessary step for effective utilization of the results of SHRP and C-SHRP for the management of rehabilitation and maintenance activities.

3/ Maintenance Budget Planning: The Standard Planning Values

The development of the maintenance workplan and budget results from interactions between different levels of management. The inventory information is updated on a yearly basis. The inventory productivity and cost information are used in the planning process. The productivity and cost information is derived from the biweekly work summary reports on the utilization of equipment and resources.

The planning process starts with the update of the highway and road physical features inventory. The inventory data are used for both planning and reporting the work. The inventory process will be discussed in some detail because it influences the statistical properties of collected data, which are of major concern.

3.1/ Inventories

The inventory process involves actual counts and field measurements of the inventoried highways and the other roadside physical features. These are done by the patrol and crew supervisors.

It is a naturally difficult task to inventory such an entity as the highways, in part due to the absence of uniformity. Thus, it is necessary to develop an appropriate classification system. The highway sections which are identical in terms of their design, traffic experience, age and environment usually have similar maintenance needs and are placed into the same group, or *road class*.

For example, MTO highways are classified using five factors, each at several levels:

1 Surface width, number of lanes; (4 categories)
2 Surface type; (from unpaved to asphalt over concrete, 6 types)
3 Shoulder type; (5 types)
4 Age of paved surface; (5 categories)
5 Average Annual Daily Traffic; (5 categories)

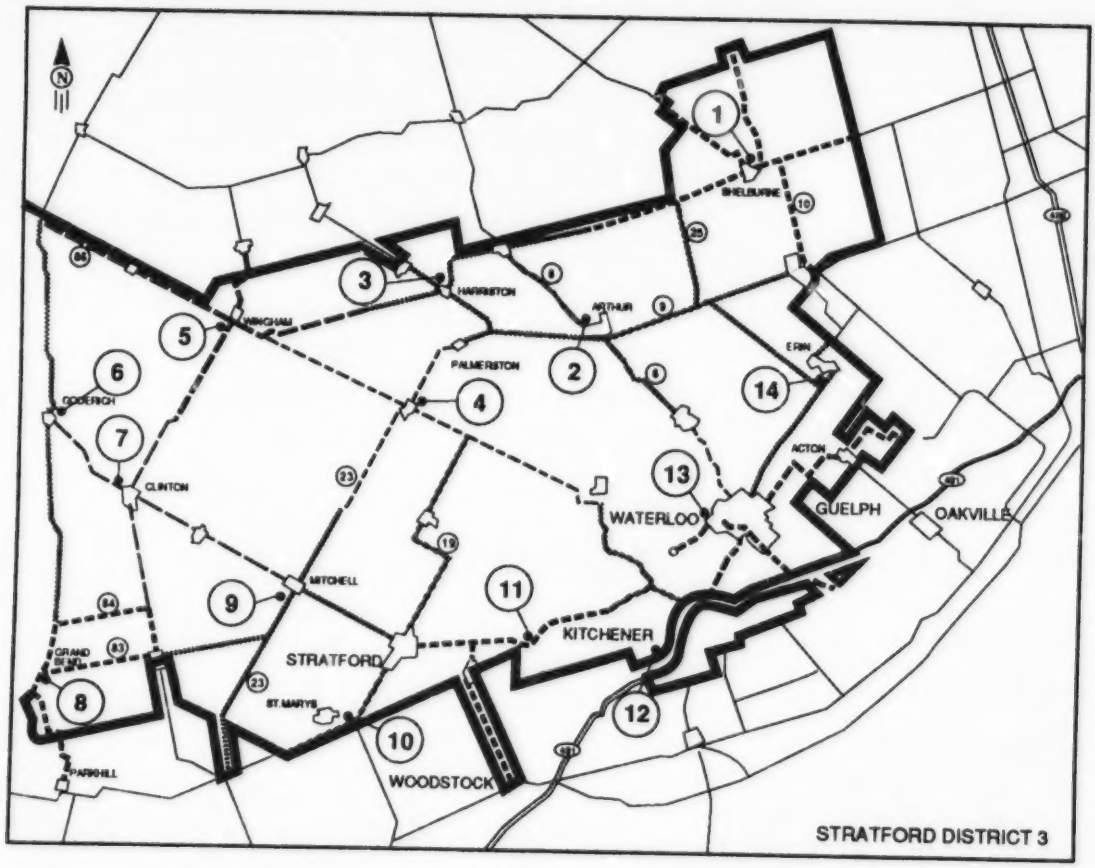
The first three factors are related to the road design, and are known to influence the demand for maintenance. The fourth factor takes into account a change in the maintenance demand due to the difference of ages of the road, and the fifth due to the difference in the rate of deterioration and the level at which the road should be maintained (quality standard).

One can question the uniformity of the selected classes as to the maintenance needs of the highways within the class; many factors, which would appear to strongly influence road maintenance needs, are not taken into account in the above classification. However, it should be kept in mind that there are only a limited number of highway sections. Generally, one can reach the desired uniformity of a class only at the expense of the number of sections in the class.

As it is, the *road class* is too fine a classification leaving too few data points in a class for some operations. Moreover, there are sets of road classes which do not differ in their maintenance demand for an operation. Consider, for example, the shoulder operations. The difference between roads of different width and age will effect the demand for shoulder maintenance probably only at extremes. Thus, road classes which do not *strongly* differ (4 or 6 lanes, asphalt or asphalt over concrete pavement surfaces) are combined into one road group for the purpose of the analysis and of standard values calculation for shoulder operations.

After the road classes are selected, the inventory is a matter of field identification and measurement. The number of equivalent two-lane kilometres of a specific highway in a specific road class within the patrol boundary is a measured patrol inventory item. Figure 1 shows the District map with the identification of the patrol jurisdictions over the highways. The maintenance inventory sections are identified and marked.

The inventory of most other items involves a simple count, and data are recorded as whole numbers.



= (e.g.) Road section assigned to patrol 4

4 = Patrol No.

= Location of patrol

6 = Hwy No.

Figure 1/ Maintenance Sections

3.2/ Work Data Reporting

The system and procedures for reporting work data are very important to the MMS. The practical difficulties in improving the existing reporting systems were previously discussed.

The reporting of maintenance work is done by each operational unit. Maintenance activities are reported for each defined maintenance operation. The operations are grouped into classes such as: pavement surface, shoulder, roadside maintenance, drainage, structures, winter maintenance operations, etc. Within each class there are several well-defined operations such as manual patching, machine patching, crack filling, etc. for pavement surface maintenance. An example of the detailed description of each operation can be found in Volume 5 of The Maintenance Manual of Ministry of Transportation of Ontario [6].

To measure the production rate of the maintenance operation, a unit of accomplishment is introduced when possible. The accomplishment is the measure of the amount of work performed, and it is selected in such a way that the amount of work done is proportional to the accomplishment. For example, for the manual patching operation, accomplishment is measured in quantity of asphaltic material used in that operation, and the unit of accomplishment is equal to 1 ton.

The amount of resources used to perform each operation is reported for each road group of each highway within the unit jurisdiction. Reporting is done daily by the staff of the maintenance units, however, only biweekly summaries of the individual reports are posted into the MMS database.

The posted data include:

- identification of the unit performing an operation;
- work location, which includes the unit identifier, the highway number and its road group; operation performed;
- biweekly accomplishment, when defined for the operation;
- normal and overhead man-hours and wages paid for these work hours;
- equipment use and its rental cost;
- quantity and cost of used materials.

3.3/ Maintenance Work Planning and Budgeting

The maintenance workplans are based on the frequency distributions of the MMS production and productivity rates data for each maintenance operation performed and each road class. The distributions are used to develop the standard planning values.

It is these *frequency models* [3], used for analysis of maintenance operations and development of the standard production rates, which are the subject of our further scrutiny. However, before discussing the problems associated with these models, the traditional process for the analysis of maintenance operations, planning and budgeting procedures will be briefly presented.

The amount of work to be done is calculated for each operation by each organizational maintenance unit. The calculations are quite simple:

the work amount required to maintain the specific inventoried asset is equal to the product of the "amount" of the inventoried asset times the standard planning value.

The amount of the assets is obtained from the inventory file.

To calculate the standard planning values, the production and productivity rates are first calculated from the MMS data. The rates are calculated as the ratios of accomplishment per quantity of assets and labour-hours or labour-cost per accomplishment or per quantity of assets. Consider, for example, a manual patching operation. The production rate is defined as the ratio of the tons of asphalt placed on the surface of a specific highway section during the year to the number of the equivalent two-lane kilometres in this section. The productivity rates are equal to a quotient of the man-hours and accomplishment or labour-cost in dollars and accomplishment.

Several assumptions are made to calculate the standard planning values. Firstly, it is assumed that the same well-defined quality standards are followed by all organizational units, meaning that the level of maintenance is the same for all units. Secondly, that uniformity exists in terms of the maintenance demand for each defined class of assets. Thirdly, it is assumed that the calculated rates belong to the same population. If these assumptions are satisfied then the production and productivity rates will form well-defined distributions.

The standard planning values are calculated as a mode of these distributions. The most frequently occurring value of production and productivity rates for the specific operation on an agency-wide basis is selected as a standard.

The standard deviations of these distributions are used to evaluate and to allow for a reasonable deviation of the standard planning value of the unit from the agency mode.

Consider now the third assumption used in statistical analysis of the data. The location of the maintenance work is known only with the precision stated above - the section of the road within the maintenance unit jurisdiction, which will be referred to as a maintenance section, see Figure 1. So, the only calculable value is

the average accomplishment per two-lane kilometres on the length of the maintenance section; where accomplishment , A, is a total yearly accomplishment value.

It is obvious that the number of equivalent two-lane kilometres, k_i, is different for each maintenance section, i. the production rate calculated as A/k_i, is the average production rate per kilometre for k_i kilometres. Thus, the calculated average production rates for different sections do not belong to the same population. In statistical terms, they are the average values obtained from samples of different sizes.

It is this specific property of the collected data which made the analysis and estimates of the standard planning values much more complex then previously believed. The number of data points available for construction of the frequency distributions is drastically reduced when one considers that only yearly average values per equivalent two-lane kilometres have a proper statistical meaning. Biweekly data cannot be utilized without obtaining additional information, namely the amount of the assets on which the work has been done during the posted period. For example, for manual patching, the length of the portion of the road on which the operation was performed during each biweekly period is required in order to make use of the biweekly accomplishment data collected.

Statistical Apropos

To clarify the data problem discussed above and to find possible ways of resolving it, the problem is reformulated as a hypothetical sampling problem. Assume that several sets of samples are drawn from the same population for the purpose of defining the distribution of some specific characteristic of the population. The samples are drawn randomly, and each has the same weight

as any other. However, each set of samples drawn from the population has a different number of items. The average values for each set are calculated, and then the original sample data are lost. However, the average values for each set and the number of the samples in each set are preserved. The problem is to define the distribution of the measured property in the population, using the retained data. The graphical illustration of the problem is presented in Figure 2. The figure shows the density function of the population distribution and density function for distribution of the averages (sample means) sample size.

For our purpose, it is important to notice that the distributions of the average values differ from the population distribution, and are different from each other when the average values are calculated from sets with different numbers of samples in each set. Thus, they cannot be used directly to construct the population distribution.

The equivalence of the problem formulated above and the problem of defining the distribution of the maintenance production rates is quite transparent. From the Borel enhanced law of large numbers [7], it follows that the distribution of the averages is tighter, i.e., it has a smaller variance than the population distribution. The larger the number of the samples used to calculate the average, the smaller the variance of the distribution of the averages, and the closer the mode to the average value for the skewed distributions.

There are no straightforward statistical approaches to solve this problem. Some assumptions about the distribution of the data within each set, the distribution of the *lost* data should be made before parameters of the population distribution can be evaluated. In the Appendix the mean and the variance of the population are derived with the assumption that the variance *within* is equal to the population variance. In other words, we assume that we are dealing with the same population in all sample sets.

Calculation of Planning Values

Presently, planning values calculation procedures use modes of the distributions of production and productivity rates. However, the available data are the averages obtained from the sets of different sample sizes. The above discussion suggests that one cannot assume that the sample means based upon different sample sizes belong to the same distribution. This makes it impossible to estimate the mode from the available data. If each of the available average values belongs to a different population, it is impossible to establish any frequency of occurrence. The example of the actual distributions for manual patching operation and the sampling property of the available data are presented in Tables 1 and 2.

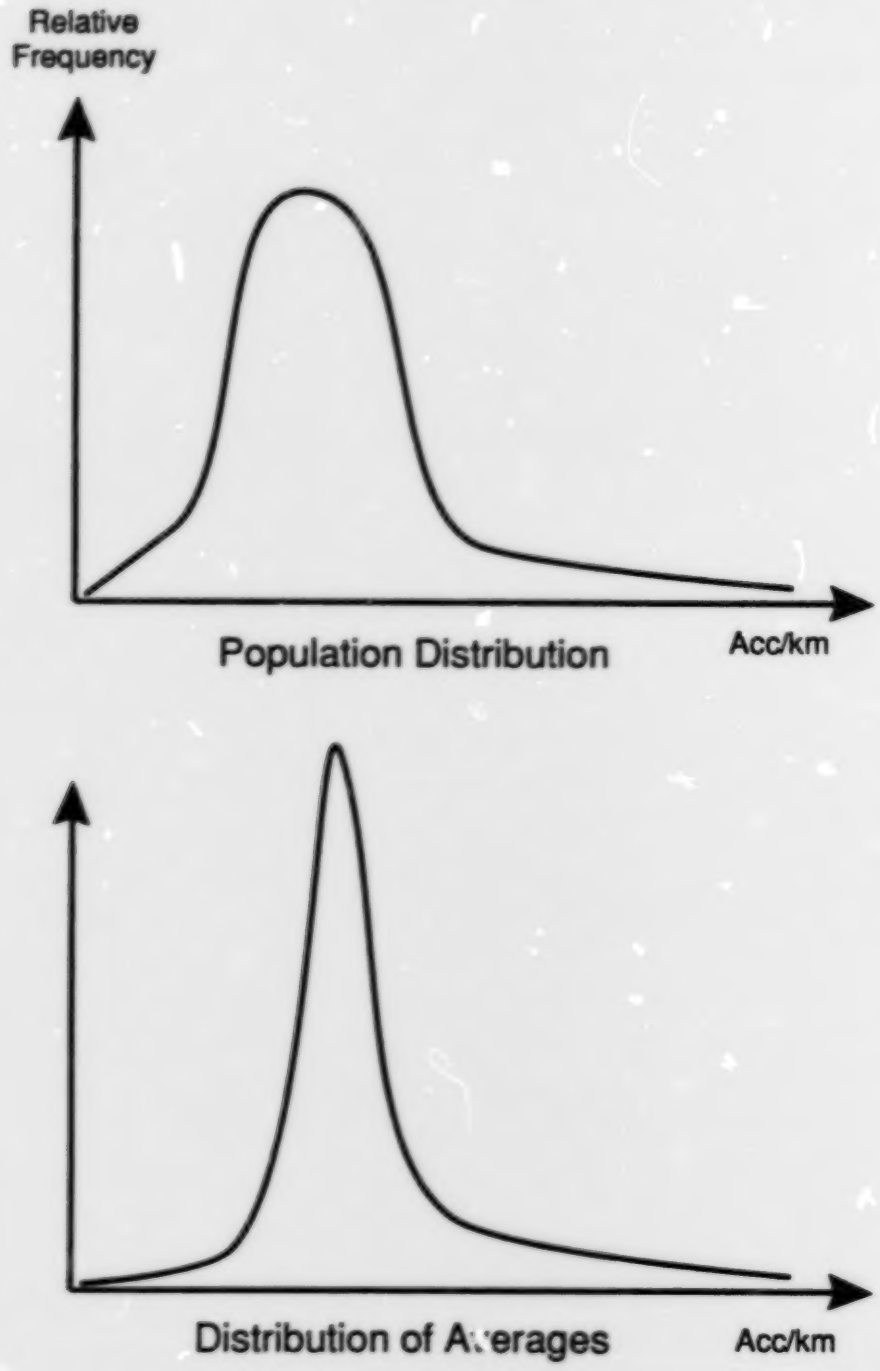


Figure 2/ Population Distribution and Distribution of Averages

Table 1

Sampling Data for Manual Patching Operation
Group 3

Length Class	Section Length km*	Number of Samples	Group Mean Accomplishment per km	Group Variance
1	2.5	1	3.07	N/A
2	10.0	8	0.14	0.02
3	20.0	13	0.23	0.10
4	37.5	30	0.29	0.07
5	62.5	13	0.23	0.05

*Section length is the mid-value of the length class range

Table 1 is based upon data for Group 3 of roads, which include several road classes. All Group 3 classes have the same pavement width, pavement surface and age levels but differ in classification by shoulder type, and AADT, where only the classes with the AADT level above 10000 are included. Sections of similar length were grouped into length classes. The average production rate calculated for each length class is assumed to belong to the same population. The section length in column 2 of Table 1 is the mid-value of the range.

The Group Mean is the mean for the section length class. The Group Variance is the variance within a length class. In other words, it is the variance of the sample means with sample size equal to section length of the class.. For the length class 2 the data are presented in Table 2. Each value of accomplishment per kilometre in Table 2 is an average per section of length ~ 10 km. It can be looked at as an average value of accomplishment per km obtained from measurements done on each kilometre of that section. The variability within the specific section is not available.

Table 2

Manual Patching Operation
Group 3, Length Class 2

Section Length	Accomplishment (tons)	Accomplishment per km
15.0	1.0	0.06
9.6	0.0	0.00
9.5	3.3	0.34
9.3	0.4	0.04
14.5	6.0	0.41
5.6	0.5	0.08
10.6	0.5	0.04
11.6	0.5	0.04

To define the mode, an assumption about the form of population distribution should be made. In cases where some of the means are calculated from the sets with the same sample size the test might be used to examine the fit of selected theoretical distribution. As it is shown in Table 1, there are 31 mean values for the length class 4. This represents a large enough sample to test the fit of the theoretical distribution. The fit of the Normal and Gamma theoretical distributions were tested and it was found that the Gamma-distribution fit the experimental data.

When means do not belong to the same population, and there is not enough data points to define the frequencies a new statistical criteria should be designed to judge the validity of a form of the theoretical distribution.

As it is shown in the Appendix, no assumptions are necessary to define the mean of the population. Assuming that each road group defines a population with a well behaved distribution, the population variance can be estimated. However, to define the mode, a strong assumption on the form of the distribution should be made.

The simple way to bypass the problem of the mode calculation is to use the mean instead. However, an interactive computer algorithm was designed to evaluate the mode, with rules for selecting the form of the population distribution. Two theoretical distributions, Normal and Gamma, are evaluated and the one which fits the data best is selected for the mode calculation.

Recognition of the proper statistical meaning of collected data influences the data analysis procedure, and changes the value of the decision variables such as standard deviation of the population production rates. This variable is used in budget allocation for a specific maintenance unit and for judgement on the unit performance. The patrols which have the average production rates for an operation outside of the reasonable range, in relation to a provincial standard, may be singled out for analysis of the reasons for their exceptionally good or poor performance. The reasonable range is defined by the population variance.

To exemplify the results of the analysis it should be noted that the data presented in Tables 1 and 2 do not include two data points (for length class 2 the data point with production rate of 4.34 tons/km and for length class 4 the point of 4.27 tons/km) which were shown to be outside the three sigma range of the population distribution and were excluded. To exlude these data points the variance of the population distribution was calculated by the method described in Appendix A. This variance is equal to 0.43. Its value is much larger than values presented in Table 1 for group vairances, as expected see Figure 2.

The proper calculation of the decision variables such as standard deviation of the production rates allows better analysis and as a result better managment of maintenance operations.

Appendix

Calculation of Population Variance

Consider a maintenance operation with the production rate defined as an accomplishment per equivalent two-lane kilometre. A maintenance section is defined as a section of a specific highway classified into a certain road group and located within the jurisdiction of the patrol. The specific highway within the patrol jurisdiction can consist of several maintenance sections. This will occur if road group classification variables for different pieces of the same highway differ significantly. It should be noted that in case of small differences in classification variables, the average values are used to classify the highway into the road group.

Using only the information in the biweekly reports, it is impossible to distinguish between the work done on any particular kilometre of the same maintenance section. Thus, the only production rate data calculable for each maintenance section are the yearly average values of accomplishment per two-lane equivalent kilometre. The production rates are calculated as the ratio of the total yearly accomplishment reported for the maintenance section per number of two-lane equivalent kilometres in it. Introducing notation for total yearly accomplishment as A_i, and for number of two-lane kilometres in the section "i", as k_i, the calculable average value is:

$$x_i = \frac{A_i}{k_i} \qquad (1)$$

Let us assume that the location of work is known to a specific kilometre of the maintenance section on which it was done. We then introduce the theoretical value x_{ij} which represents an amount of work done on the kilometre "j" of the section "i"; the amount of work is measured in accomplishments. Then, the above average can be written as:

$$x_i = \frac{\Sigma_j x_{ij}}{k_i} \qquad (2)$$

where $A_i = \Sigma_j x_{ij}$ (3)

The provincial average for a road group, μ, can be calculated as:

$$\mu = \frac{\Sigma_i A_i}{\Sigma_i k_i} = \frac{\Sigma\Sigma x_{ij}}{N} \tag{4}$$

where $N = \Sigma_i k_i$ (5)

Thus, N is the total number of two-lane equivalent kilometres of highway in a road group.

The population variance σ^2 for a finite population by definition equals:

$$\sigma^2 = \frac{\Sigma_i \Sigma_j (x_{ij} - \mu)^2}{N - 1} \tag{6}$$

Adding and subtracting x_i, then opening the brackets and simplifying the definition, equation (6) can be rewritten in the following form:

$$\sigma^2 = \frac{1}{N - 1}\left(\Sigma\Sigma\left(x_{ij} - x_i\right)^2 + \Sigma\Sigma\left(x_i - \mu\right)^2\right) \tag{7}$$

By multiplying and dividing the first member of the sum in the brackets by k_i-1 and summing by j the second equation (7) will take the form:

$$\sigma^2 = \frac{1}{N - 1}\left(\Sigma_i \frac{\Sigma_j \left(x_{ij} - x_i\right)^2}{\left(k_i - 1\right)}\left(k_i - 1\right) + \Sigma_i \left(x_i - \mu\right)^2 k_i\right) \tag{7}$$

Let us introduce the sample variance s_i^2, and substitute it into equation (7):

$$s_i^2 = \frac{\sum_j \left(x_{ij} - x_i\right)^2}{k_i - 1} \qquad (8)$$

The value of s_i^2 is a sample estimate of population variance σ^2. As discussed above, this value cannot be obtained from the Maintenance Management System data. An assumption should be made about the character of the distribution within each sample. For example, one can assume that the accomplishments for each kilometre of the maintenance section are equal, then $s_i^2 = 0$.

We assume that if xij values were measured, the accomplishment for any kilometre "i" of any maintenance section within the specific road group "j", they would belong to the same population. Then the sample variance is an estimate of the population variance. We assume that the sample variance is equal to the evaluated population variance. For the large section, this assumption probably holds quite well. That is, the sample estimate of the variance is close to population variance, but it can deviate strongly for small sections. The total number of equivalent two-lane kilometres in the maintenance section, ni, is an equivalent of the sample size in this case. Substituting σ^2, instead of s^2 into equation (9) and simplifying, the population variance will be equal to:

$$\sigma^2 = \frac{1}{n - 1} \sum_i \left(x_i - \mu\right)^2 k_i \qquad (9)$$

where n is number of maintenance sections within the road group.

If the sections are of equal size, so k_i=k=constant for any i, it will be reduced to a well-known statistical relation between the variance of the population distribution and the variance of the distribution of average values.

$$\sigma^2 = S_m^2 k$$

where S_m^2 is the variance of the population of average values.

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